Title: The Future Northeast Atlantic Wave Energy Potential under Climate Change

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The Future Northeast Atlantic Wave Energy Potential under Climate Change

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ABSTRACT

The potential changes to the wave energy flux and wave directionality of the Northeast Atlantic region towards the end of the 21st century are examined using a two-grid WAVEWATCH III model ensemble, driven by the EC-Earth global climate model under Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5. A decrease in the wave energy flux across all seasons and a change in the directionality (mean and peak wave direction) was found, with both clockwise and anticlockwise rotations of up to 10° in some regions of the Northeast Atlantic by the end of the century.

KEY WORDS: Ocean renewable energy; wave climate; wave projections; WAVEWATCHIII; Northeast Atlantic; wave energy flux; wave direction.

INTRODUCTION

The world's oceans contain vast quantities of untapped ocean renewable energy and more so in areas where the surface wind blows over long distances. One of these areas is certainly the western coast of Europe which is at the end of a long fetch i.e. the North Atlantic Ocean, which then makes Ireland ideally placed to harness these resources, as well as a promising location for the future deployment of Wave Energy Converters (WECs). North Atlantic swells and mid-latitude cyclones propagate eastward towards the coastline of Ireland creating highly energetic and waves of varying sizes (Gallagher et al, 2016a). Typical annual mean significant wave heights (Hs) in the Irish Sea are from 1–2 m and to 3–4 m off the Atlantic coast of Ireland (Gallagher et al., 2013, 2014b). Likewise, several large waves and sea-states have been recorded and modelled off the south and west coasts of Ireland (Atan et al., 2016, Flanagan et al., 2016, Fedele et al.,2016, Clancy et al., 2015, Clancy et al., 2016, Gallagher, et al., 2014b, Gallagher et al, 2016b). Wave energy is a largely unused energy source. Harnessing such energy has the potential to supply a significant part of electrical energy consumption. With the continuing rise in the price of energy and the rise in demand for cleaner energy, the extraction of wave energy is potentially significant for Ireland, because of its vulnerability to energy price and supply uncertainties.

With wind as a major forcing factor in the generation of surface waves and considering changes in the atmospheric circulation, changes in the wave climate are expected. A number of studies show results for measured or modelled trends in wind speed and significant wave height in different regions with different time periods observed, see for example Fan et al. (2014). These studies are often limited spatially and temporally. Studies have shown increases in the mean significant wave height Hs (Bacon et al., 1991) and wind speed (Young et al., 2011) from the middle of the last century until the beginning of the 21st century and a change from increase to decrease in this century (Dobrynin et al., 2012). Dobrynin et al. (2012) concluded that the projected wave heights (4.9% decrease in the North Atlantic) at the end of the 21st century are within natural variability. The wave climate of the Northeast Atlantic has been shown to be highly influenced by large-scale pressure and circulation anomalies or teleconnections, such as the North Atlantic Oscillation, creating a variable climatology on time-scales of decades or more (Atan et al., 2016, Gallagher et al., 2014a). For this reason, we examine time periods of 30 years in length, to account for decadal-scale variability.

The objective of this paper is to assess the projected changes of the wave energy potential caused by the climate change into the future. We examine the potential changes in both the wave energy flux and wave directionality by season and inter-annually, in order to examine changes in the wave energy variability, and the energy extraction potential for Ireland for the end of the 21st century. This has been done by estimating the changes in the wave energy flux, direction and peak direction outputted from a two-grid WAVEWATCH III (Tolman, 2014) model ensemble, focusing on the Northeast Atlantic region.

The goal of this study is to analyse projected wave changes for the RCP4.5 and RCP8.5 with three members in each RCP wave model ensemble using the EC-Earth global climate model to force the WAVEWATCHIII (WW3) wave model. We are interested in quantifying changes in the wave energy flux, mean wave and peak, focusing on the Northeast Atlantic region. A comparison was performed between 30-year future period (2070-2099) and the historical period (1980-2009) for two greenhouse gas emission scenarios RCP4.5 and RCP8.5.

We are expanding the research by Gallagher et al. (2016b, 2016c) by looking at a larger area (the grid of the WW3 model that covers the

Northeast Atlantic) and by including all seasons in the analysis. The reason behind the decision to look at a larger region is the interest in the nearshore and offshore areas, deep water applications and west coast of Scotland as an area with a high wave energy potential. Unlike Gallagher et al. (2016b, 2016c), we are primarily interested in the application to the renewable energy sector.
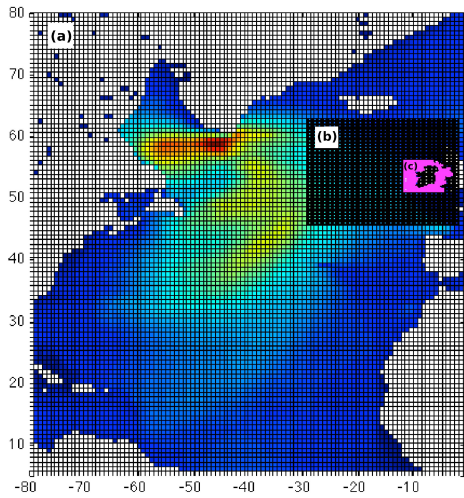

Figure 1: The three -wave model grids used in Gallagher et al. (2016b). This study focuses on the wave energy potential of the middle grid b).

MODEL DETAILS

EC-Earth Model

CMIP5 (Coupled Model Intercomparison Project Phase 5) (Taylor et al., 2012) experiments are created to address scientific questions that arose as part of the IPCC AR4 (the Intergovernmental Panel on Climate Change 4th Assessment Report) process, to improve understanding of climate, and to provide estimates of future climate change. The CMIP5 is a framework for model runs which involves 20 climate modelling groups and huge variety of Earth System Models (see Wang et al., 2015). Earth System Models (EMS) are climate models that include representation of the biogeochemical cycles important to climate change.

The EMS model that has been chosen is the EC-Earth model (Hazeleger et al., 2010, 2012). The EC-Earth model mean sea level pressure compared favorably to the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim re-analysis data set (Dee et al., 2011). The EC-Earth model is able to portray the high wind speed and extratropical cyclone characteristics when compared to ERA-Interim.

EC-Earth version 2.3 consists of an atmosphere-land surface module coupled to an ocean-sea ice module (Hazeleger et al., 2010, 2012) with the Ocean Atmosphere Sea Ice Soil coupler (OASIS) version 3 (Valcke, 2006). The atmospheric component of this model is based on the Integrated Forecasting System with a spatial resolution of 125 km and 62 vertical layers up to 5 hPa. The oceanic component is the Nucleus for European Modelling of the Ocean version 2 with a resolution of 110 km (Madec, 2008) with 42 vertical layers and finally the Sea-Ice component is the Louvain-la-Neuve Sea Ice Model (LIM) version 2 (Fichefet and Maqueda,1997).

The EC-Earth model has been run with two future scenarios Representative Concentration Pathways (RCPs) RCP4.5 and RCP8.5, where RCP4.5 is medium/high stabilized at approximately 4.5 W/m^2 after

2100 and RCP8.5 is high pathway with a radiative forcing that reaches over 8.5 W/m^2 by year 2100 (Moss et al., 2008). There are three realizations (X=1,2,3), each driven by a separate EC-Earth ensemble member, which make up the wave climate ensemble: each containing one historical and two future simulations corresponding to the above-mentioned RCPs. The historical period is from 1980 to 2009 and the future period is from 2070 to 2099. To conclude there are nine 30-year data sets (meiX, me4X, me8X) and with the ERA-Interim hindcast, ten simulations in total.

WAVEWATCHIII (WW3)

WW3 is a third generation 'phase-averaged' model that solves the wave-action balance equation where conservation of the action density is balanced by source terms that represent physical processes that generate or dissipate waves. The model has been forced with EC-Earth model 10 m winds and sea ice fields and ERA-Interim data.

The model was run with three grids (see Figure 1). The grid a) covers the North Atlantic with a resolution of 0.75° x 0.75°. Grid b) covers the Northeast Atlantic with a resolution of approximately 25 km (0.25° x 0.25°). The grid around Ireland is an unstructured grid with a resolution from 15 km offshore to 1 km nearshore but was not the focus of this study as we concentrated our analysis on the larger regional grid b). Grid a) and b) are two way nested. The unstructured grid was feed with wave spectra from grid b). The model was set to have 36 frequencies (starting at 0.0345 Hz) and 36 directions. Input and dissipation term was set as in TEST 451 (Ardhuin et al.,2010). This research studies the historical and future period of hourly wave energy flux, mean wave and peak direction data over the Northeast Atlantic.

The model was validated by comparing the historical EC-Earth WW3 runs and ERA-Interim hindcast. The ERA-Interim driven WW3 run was compared to buoy measurements as well and showed a good correlation. For further details see Gallagher et al. (2016b). In addition, we have expanded this validation by comparing the ERA-Interim driven WW3 run with the historical EC-Earth WW3 runs for the wave energy flux, mean wave direction and peak wave direction. The focus of our analysis was on the middle grid (see Figure 1(b)), which covers a larger region in the Northeast Atlantic, as opposed to the grid only around the nearshore of Ireland (see Figure 1(c)), as this provides an opportunity to examine on a regional scale both nearshore and offshore areas, deep water applications and also the west coast of Scotland and France as an area with a high wave energy potential as well as Ireland.

We are interested in wave energy flux, mean wave direction and peak direction. Wave energy flux and peak direction i.e. direction of the most energetic wave that can damage WECs are evidently important for WECs. Mean wave direction gives a direction that is most common for the bulk of waves coming to the area of interest. The change in wave energy directionality (mean direction) affects the site selection, design, and performance of nearshore WECs (Gallagher, 2013). The change in the direction can mean a different source of the wave energy coming to Ireland.

METHODOLOGY

From hourly outputted data over the 30 year periods of interest, we have obtained the 30-year means (annual and seasonal) for all wave model runs. We have then calculated the ensemble means from these 30-year means and compared the historical ensemble mean to each of the two future ensemble means (from RCP4.5 and RCP8.5) to examine how the wave climate may change, on average towards the end of the century.

Directional Statistics

The mean of an array of directions can be calculated using the following formulas:

$$X = \frac{1}{n}\sum_{i=1}^{n} \cos \alpha_i \qquad (1)$$

$$Y = \frac{1}{n}\sum_{i=1}^{n} \sin \alpha_i \qquad (2)$$

$$R = \sqrt{X^2 + Y^2} \qquad (3)$$

$$\cos \bar{\alpha} = \frac{X}{R} \qquad (4)$$

$$\sin \bar{\alpha} = \frac{Y}{R} \qquad (5)$$

$$\theta = atan2\left[\frac{\sin \bar{\alpha}}{\cos \bar{\alpha}}\right] \qquad (6)$$

Where atan2 is defined as:

$$atan2(y,x) = \begin{cases} atan\left(\frac{y}{x}\right) & x > 0 \\ \pi + atan\left(\frac{y}{x}\right) & y \geq 0, x < 0 \\ -\pi + atan\left(\frac{y}{x}\right) & y < 0, x < 0 \\ \frac{\pi}{2} & y > 0, x = 0 \\ -\frac{\pi}{2} & y < 0, x = 0 \\ 0 & y = 0, x = 0 \end{cases} \qquad (7)$$

And where directions (α_i) are expressed in radians, n is the length of the array of directions and θ is the mean direction (Berens, 2009, Hintze, 2015).

Standard Deviation

The standard deviation for the wave energy flux has been normalized and presented to see how the wave energy varies annually and by season. This can be seen as a measure of the interannual variability of the wave energy resource and a way to examine how much the resource can vary year-to-year. Note: the standard deviations presented in this study have been calculated between the 30 yearly annual and seasonal means and not over the hourly timeseries.

VALIDATION

Cge – Wave Energy Flux

In Figure 2, it can be seen that the data from WW3 driven by ERA-Interim and by EC-Earth for the 1980-2009 period compare well. The mean wave energy flux (CGE) annual and seasonal (winter = December, January, February; summer = June, July August; spring = March, April, May; and autumn = September, October, November) climate patterns are captured broadly when compared to the ERA-Interim driven hindcast. There is only a slight overestimation in the winter period and in the annual ensemble mean, with the historical ensemble estimating a larger area of the highest winter CGE values (see Figure 2(g)).

Dir – Mean Wave Direction and Dp – Peak Direction

Both mean wave direction and peak wave direction (not shown) compare well with the ERA-Interim driven WW3 run as can be seen in Figure 3. For brevity, we only displayed the annual, winter and summer directions, as these display the full variability of these parameters. The Figures for spring and autumn (not shown) for both DIR and DP show similar results and are not presented here.

In summary, we have expanded on the validation carried out in Gallagher et al. (2016b) where an ERA-Interim driven WW3 hindcast run was compared to buoy measurements and showed that they correlated well. The mean and 95th percentile of annual and seasonal significant wave height means were also compared for the ERA-Interim driven versus the EC-Earth driven historical WW3 runs in Gallagher et al. (2016b). We have further developed on the verification of the dataset by comparing the annual and seasonal means of CGE, mean wave direction and peak wave direction for the ERA-Interim driven versus the EC-Earth driven historical WW3 simulations as these are the relevant parameters for this study. We found that overall, the EC-Earth driven WW3 simulations compared well to the ERA-Interim driven runs, and show that the EC-Earth driven WW3 runs are able to acceptably capture the present wave climate (1980-2009) giving confidence to the projected changes found in the future (2070-2099) WW3 simulations.

RESULTS

Cge – Wave Energy Flux

Looking at the Figure 4 (a), (b), (c), (d) and (e) we can see that the WW3 model is showing the expected differences in wave energy flux throughout the seasons in the period from 1980 to 2009, with winter having the most energy and summer the lowest. Wave energy flux reaches values over 150 kW/m in a relatively large area near the whole west coast of Ireland and North Scotland. The maximum summer energy is just around 25 kW/m.

The annual wave energy flux reaches around 80 kW/m offshore to the west of Ireland and Scotland. In fact, a large continuous region with mean annual CGE values over 50 kW/m near coastal areas can be found stretching from the north of Scotland to the west coast of Brittany, France which is also evident in the ERA-Interim driven WW3 hindcast shown in Figure 2 (a). Mean autumn and spring CGE values exhibit slightly less than the annual mean values.
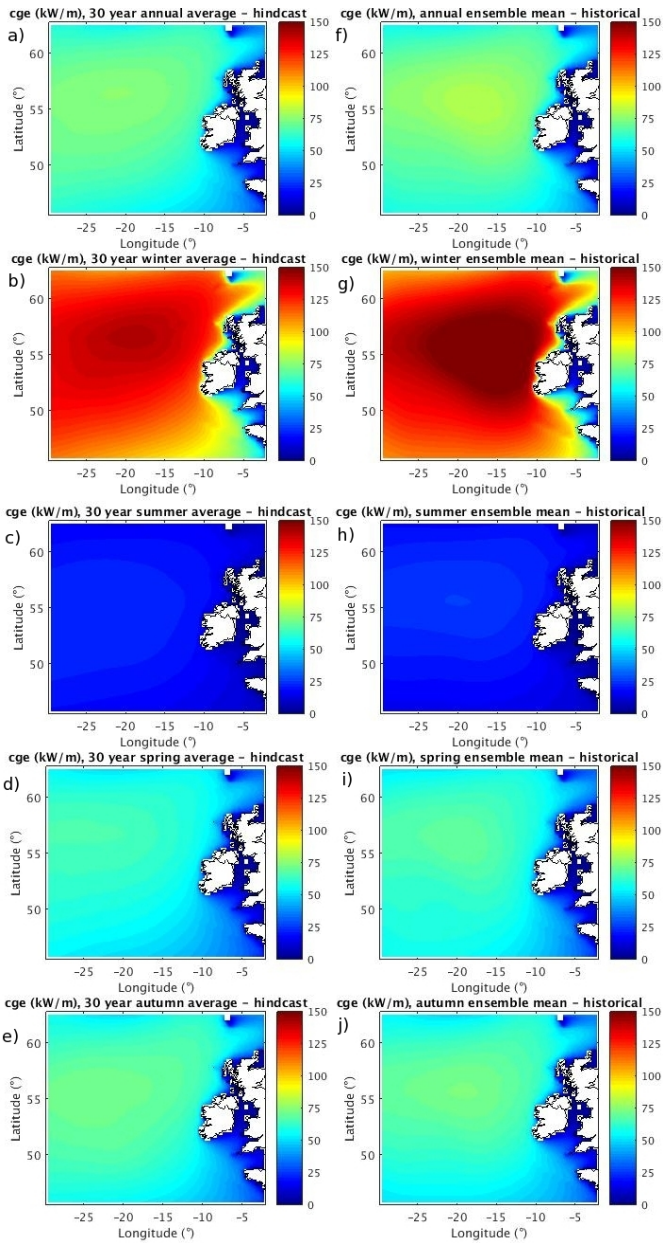
Figure 2: Comparison between ERA-Interim driven hindcast (a) annual, (b) winter, (c) summer, (d) spring, and (e) autumn and ensemble mean (f) annual, (g) winter, (h) summer, (i) spring and (j) autumn of the historical EC-Earth driven wave model, both from 1980-2009 for the wave energy flux.

Figure 5 (f), (g), (h), (i) and (j) shows a smaller change in the CGE for the future period compared to Figure 5 (k), (l), (m), (n) and (o) which can be expected since RCP4.5 is medium/high and RCP8.5 is a high pathway, but what applies to both pathways is that they are showing a decrease of CGE by the end of the 21st century except in the northern part of our area of interest in summer time. Though the largest relative change is shown in summer (40% decrease) it needs to be taken into account that the energy in the summer is much lower compared to other seasons, so the largest decrease in absolute magnitude terms is actually going to be in winter (up to 30 kW/m). The maximum increase in the summer time in the north of the observed area is 2 kW/m.
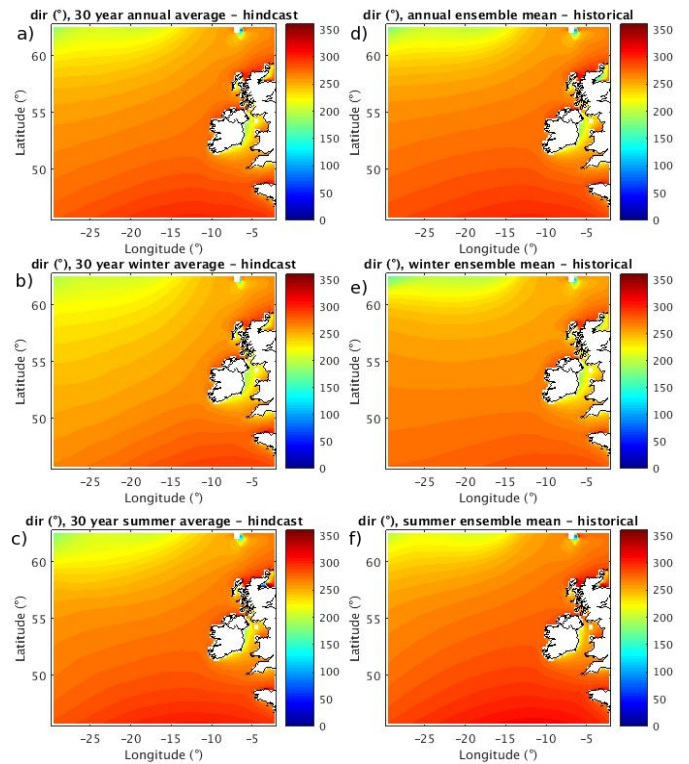

Figure 3: Comparison between ERA-Interim driven hindcast (a) annual, (b) winter and (c) summer and ensemble mean (d) annual, (e) winter and (f) summer of the historical EC-Earth driven wave model, both from 1980-2009 for the mean wave direction.

The signal for changes in CGE in spring and autumn was less robust or clear, with large areas of the decrease in GCE found not to be statistically significant by our metric, particularly in spring off the west coast of Ireland and Scotland under both RCP scenarios as can be seen in Figure 4 (j) and (o).

Figure 5 (a), (f) and (k) shows that the annual standard deviation for CGE ranges from 10 to 20% for the historical and two future periods. The highest values can be seen in summer for RCP8.5 between the islands around 40% but it is in a concentrated area where in spring we have larger area with around 30-35% standard deviation. In most other cases and areas the standard deviation ranges between 15% and 25%. We can see lower values for standard deviation in the future especially for RCP8.5 indicating less seasonal variability than the present climate.

Dir – Mean Wave Direction and Dp – Peak Direction

Figure 6 (a), (b), (c), (d), and (e) shows that the mean wave direction for all seasons and annually ranges from around 250° to 270° except in the north part of the observed area where it is around 200° to 230° for the historical period. In the future, Figure 6 (f), (g), (h), (i) and (j) (under the RCP4.5 scenario) shows a smaller change in the DIR compared to Figure 6 (k), (l), (m), (n) and (o) (under the RCP8.5 scenario), which has more concentrated areas of change in the direction. However, what applies to most of the subplots of Figure 6 generally is that they show a rotation of DIR in the anticlockwise direction by the end of the 21st century in the
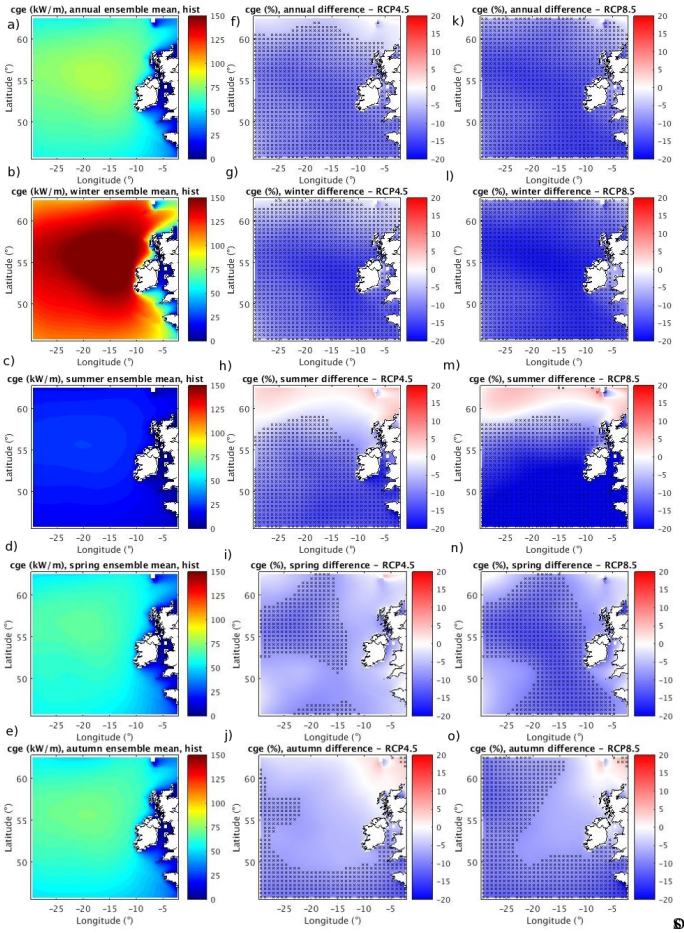
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Figure 4: Ensemble mean (a) annual, (b) winter, (c) summer, (d) spring, and (e) autumn CGE (kW/m) for the historical period (1980–2009). Projected changes (%) of CGE for the period 2070–2099 relative to 1980–2009 for RCP4.5 (f) annual ensemble mean, (g) winter, (h) summer, (i) spring, (j) autumn and for RCP8.5 (k) annual ensemble mean, (l) winter, (m) summer, (n) spring and (o) autumn ensemble mean. Stippling indicates where the % changes in the future CGE ensemble mean exceed twice the inter-ensemble standard deviation.

south-west and north-east part of the area and a clockwise change of DIR in the north-west and south-east part of the model domain. The summer subplot for RCP8.5 (Figure 6 (m)) shows large areas where DIR rotates clockwise by more than 10° and the winter subplot for RCP4.5 (Figure 6 (g)) shows smaller areas where DIR rotates anticlockwise by around 10°. This represents evidence of a southerly shift in the mean wave direction off the west of Ireland in winter. The majority of the subplots (see Figure 6) show large areas where DIR rotates anticlockwise by less than 5°.

Figure 7 (a), (b), (c), (d), and (e) shows that the peak wave direction for all seasons and annually ranges from around 250° to 270° except in the north-west part of the observed area where it is around 200° to 230° for the historical period. Most of the subplots (see Figure 7) exhibit large areas where DP changes with a anticlockwise rotation of 0° to 5° (with the highest change in winter) and smaller areas where DP changes with a clockwise rotation of 2.5° to 5° (with the largest change in spring in the north-west area).
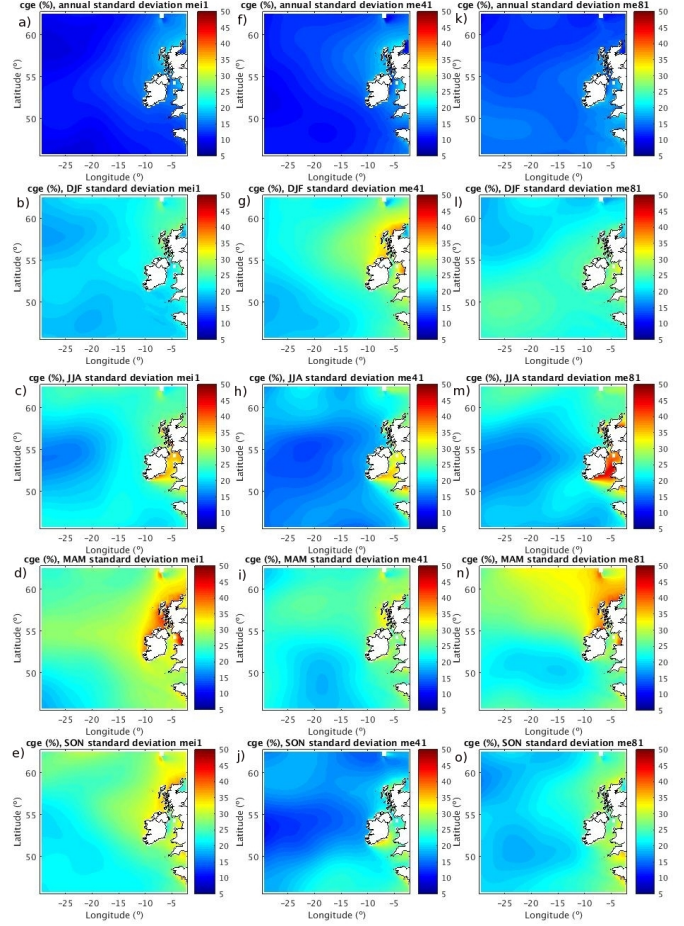

Figure 5: Standard deviation (a) annual, (b) winter, (c) summer, (d) spring, and (e) autumn CGE (kW/m) for the period 2070–2099 RCP8.5 for X=1 i.e. first realization. Standard deviation (f) annual, (g) winter, (h) summer, (i) spring, and (j) autumn CGE (kW/m) for the period 2070–2099 RCP8.5 for X=1. Standard deviation (k) annual, (l) winter, (m) summer, (n) spring, and (o) autumn CGE (kW/m) for the historical period (1980–2009) for X=1.

CONCLUSION AND DISCUSSION

We carried out an analysis of the wave energy flux (CGE) and wave directionality by season and inter-annually, outputted from a two-grid WAVEWATCH III model ensemble, focusing on the Northeast Atlantic WAVEWATCHIII wave model was forced with EC-Earth global climate model and ERA-Interim fields and they were compared for the period region. Two datasets (RCP4.5 and RCP8.5) for the 30-year future period 2070-2099 were compared to the dataset for the historical period 1980-2009 with three members in each wave model ensemble.

The EC-Earth global climate model estimates an overall decrease in the seasonal means and extreme percentiles of 10 m winds over the North Atlantic Ocean by the end of the 21st century and subsequently of the wave energy flux off the western seaboard of Ireland, particularly under RCP8.5 in both summer and winter. Overall, we found a general decrease in the CGE across all seasons, but much less so in spring and autumn, and a change in the directionality with both a clockwise and anticlockwise rotation of up to 10° or more in regions in the Northeast Atlantic.

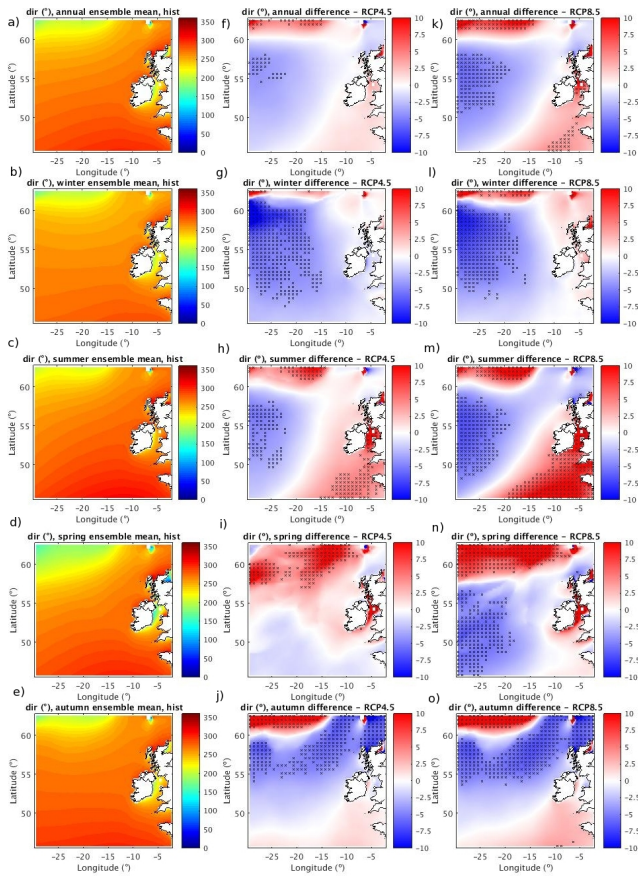The increase in CGE in the north of the domain in summer (as shown in

Figure 6: Ensemble mean (a) annual, (b) winter, (c) summer, (d) spring and (e) autumn DIR (°) for the historical period (1980–2009). Projected changes of DIR (°) for the period 2070–2099 relative to 1980–2009 for RCP4.5 (f) annual ensemble mean, (g) winter, (h) summer, (i) spring, (j) autumn and for RCP8.5 (k) annual ensemble mean, (l) winter, (m) summer, (n) spring and (o) autumn ensemble mean. Colorbar shows the magnitude of the changes (°), with positive (negative) values showing a clockwise (anticlockwise) rotation in the annual/seasonal mean wave direction. Stippling indicates where the % changes in the future DIR ensemble mean exceed twice the inter-ensemble standard deviation.

Figure 4 over both RCP scenarios) is related to the increase in 10 m winds found in Gallagher et al. (2016b) to the south of Iceland. All the changes in Figure 4 are linked to changes in the North Atlantic surface winds and storm tracks as can be seen in Gallagher et al. (2016b).

In most subplots, highest standard deviation for CGE (Figure 5) is close to the islands and it is connected to the fact that wind is too coarse to resolve the Irish Sea properly as well as the WAVEWATCHIII grid of interest (see Figure 10 in Gallagher et al, 2014a). For this reason, we have concentrated on the west coast of Ireland and because the Irish sea is a low energy area. It is known that the west coast is mostly dominated by swells and the east coast by wind seas.

Figure 6 (a), (b), (c), (d), and (e) confirms the fact that the wave energy arriving on the Irish coast approaches the coast mostly with a direction of 240 - 300° with 270° predominating (SEAI, 2016). The simulations also show evidence of a southerly shift in the mean DIR and DP in winter in the west of the domain towards the end of the century under both RCP scenarios. Generally, the projected changes in DIR and DP were found to
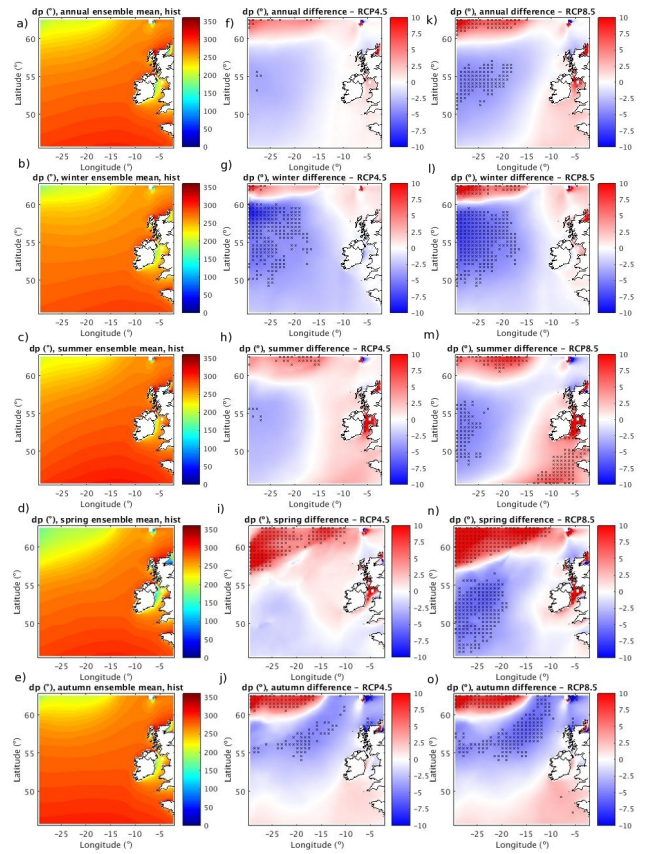
Figure 7: Ensemble (a) annual, (b) winter, (c) summer, (d) spring and (e) autumn DP (°) for the historical period (1980–2009). Projected changes of DP (°) for the period 2070–2099 relative to 1980–2009 for RCP4.5 (f) annual ensemble mean, (g) winter, (h) summer, (i) spring, (j) autumn and for RCP8.5 (k) annual ensemble mean, (l) winter, (m) summer, (n) spring and (o) autumn ensemble mean. Colorbar shows the magnitude of the changes (°), with positive (negative) values showing a clockwise (anticlockwise) rotation in the annual/seasonal peak direction. Stippling indicates where the % changes in the future DP ensemble mean exceed twice the inter-ensemble standard deviation.

have greater magnitude and larger areas of significance (stippled areas) under the RCP8.5 scenario, although these changes were less robust than CGE, where large areas of significance were found across most seasons.

Despite the decrease in wave energy, the simulations show a likely continuing huge energy resource off the coast of Ireland and Scotland (in excess of 70 KW/m annually), It is also worth noting that there is a continuous stretch of ocean along the Northeast Atlantic western seaboard, stretching from the north of Scotland down to the west coast of Brittany, France, which has mean annual CGE values close to the shore exceeding 40-50 kW/m, even if the projected decreases in CGE are realized. However, this study also shows that the resource. However, this study also shows that the resource is highly variable which should be taken into account when planning WEC deployment and ocean energy extraction.

Though Earth System Models have shown an improved performance in the simulation of the Earth's climate and changes (Flato et al., 2013), uncertainty in the ensemble of climate simulations can't be avoided. The uncertainty includes scenario, model and method uncertainty (Wang and Swail, 2006). The signal of climate change needs to be separated from the internal variability of the climate system with a related quantified

uncertainty (Wang and Swail, 2015). For this reason, we have analysed where changes in a certain parameter exceed twice the inter-ensemble standard deviation (test of significance), the same metric that was used in a previous analysis of this region by Gallagher et al. (2016b). Analysis by Gallagher et al. (2016b) is similar to the test for significance used in Hemer et al. (2013), although they used a multi-model five member ensemble. It needs to be taken into an account that we have observed a small number of ensembles.

Future work will be to examine in detail the percentage of time for which energy extraction is possible. This provides a useful analysis of locations around the coast of Ireland for long-term WEC deployment and how these might be affected in the future.

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